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UNITED STATES
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J. A. KRUG, SECRETARY

BUREAU OF MINES
JAMES BOYD, DIRECTOR

INFORMATION CIRCULAR

MAKING IRON POWDER IN THE TUNNEL KILN

BY

V. H. GOTTSCHALK

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MAKING IRON POWDER IN THE TUNNEL KILN[1]

V. H. Gottschalk[2]

INTRODUCTION

Among the procedures developed by the Germans for providing the tonnage of iron powder needed to make rotating bands for artillery shells is the use of a ceramic tunnel kiln, not only for finishing the reduction of centrifugal powders but also for making so-called "brickyard sponge iron," which, after crushing and grinding, seems to yield a product suitable for powder-metallurgical purposes.

The final report issued jointly by the German Powder-Metallurgical Society (DPG) and the Chemical-Metallurgical Branch of the Research Department of the Metallgesellschaft, Inc. (ZFC of MG) gives the available details of this procedure, which may be regarded as a further development of the process in commercial use since 1911 at a ceramic plant in Hoeganaes, Sweden. The Bureau of Mines' wartime development of the Hoeganaes process also culminated in the adaptation of ceramic tunnel kilns for carrying out the solid-carbon reduction of iron ores, and comparison with the German technique should further advance the art.

This information circular is issued as a supplement to Bureau of Mines reports of investigations Nos. 3819,[3] 3822,[4] 3841,[5] and 4271,[6] on brickyard sponge iron and is based on four German reports entitled "Making Iron Powder in the Tunnel Kiln," translated from FIAT microfilm reel H-46, frames 9190-9209, 9280-9299, 9339-9357, and 9377-9384 (PB L 70042), which represent the four original research reports, Nos. 2005, 2008, 2010, and 2012, respectively, of the Metallgesellschaft, Inc.

1/ The Bureau of Mines will welcome reprinting of this paper, provided the following footnote acknowledgment is made: "Reprinted from Bureau of Mines Information Circular 7473."

2/ Senior physicist, Bureau of Mines, College Park, Md.

3/ Walker, J. P., Reduction of Iron Ore in Clay and Steel Containers (Saggers): Bureau of Mines Report of Investigations 3819, 1945, 30 pp.

4/ Ross, Donald W., Production of Sponge Iron in a Shale-Brick Plant: Bureau of Mines Report of Investigations 3822, 1945, 27 pp.

5/ Smith, Kenneth M., and Burton, S. E., Manufacture of Sponge Iron in Periodic Brick Kilns: Bureau of Mines Report of Investigations 3841, 1945, 38 pp.

6/ Gottschalk, V. H., Beebe, E. S., and Cole, Richard S., Manufacture of Sponge Iron in Ceramic Tunnel Kilns: Bureau of Mines Report of Investigations 4271, 1948, 25 pp.

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The descriptions of German methods for making iron powders and their use in the manufacture of shell-rotating bands, as reported by Comstock,7/ Krebs,8/ and Ivery,9/ indicate that the centrifugal powders made by DPG suffered in competition with iron powders made by other methods because of the oxide content unavoidably acquired during manufacture. Apparently, this excess of oxide could not be removed at a rate demanded by the war emergency by reducing in hydrogen, and this led to experiments with solid-carbon reduction in a ceramic kiln found available at the North German Stoneware Co., Inc., in Bremen.

THE TUNNEL KILN

This indirectly fired, muffled tunnel kiln of Dressler design was 50 meters (164 feet) long and operated with 27 cars that were 173 cm. (5.68 feet) long and 100 cm. (3.28 feet) wide, loaded to a height of 110 cm. (3.61 feet), each with 60 ceramic containers (so-called "saggers," made from clay-grog mixture). The saggers normally were 45 x 22 x 20 cm. (approximately 18 inches long, 8-1/2 inches wide, and 8 inches high), corresponding to a volume of about 13 liters (3.434 U. S. gallons, or 0.459 cubic foot). There is a space under the car tracks that is sealed against the actual furnace by means of sand, thus protecting the lower parts of the cars from excessive heat.

The kiln is heated by producer gas of about 1,200 heat units per cu. m. (134.9 B.t.u. per cu. ft.) generated from coke in a revolving-grate producer. To generate 1 cu. m. of gas required 0.250 kilograms of coke and 0.1 kilogram of steam for saturating the blast at about 65°C. (15.6 lb. coke and 5.8 lb. steam per 1,000 cu. ft.). The producer gas was led to the heating flues in a primitive way by forcing it at a slight pressure (2 to 4 mm. of water column = 0.079 to 0.157 inch) through a horizontal slotted burner plate situated in the middle of the furnace on both sides. Air for combustion was blown over the burner plate by means of a fan at 1 to 2 mm. (0.04 to 0.08 inch) water pressure. The two heating flues are connected to a high chimney the draft of which may be regulated by dampers at the ends of the flues.

As reduced iron is readily oxidized, a protective atmosphere in the muffle seemed imperative, and this, again, called for "locks" at both ends of the kiln to prevent access of air while cars were pushed in or pulled out. In addition, a system of air-cooled pipes was built into the discharge end of the kiln to lessen the chance of reoxidation during cooling.

7/ Comstock, Gregory J., German Powder Metallurgy: FIAT Final Report No. 772 (PB L 39354-R), June 17, 1947, pp. 52-74.

8/ Krebs, Heinrich L., Sintered Iron Shell Rotating Bands: FIAT Final Report No. 979 (PB L 78261), March 19, 1947, 8 pp.

9/ Ivery, W., The Production of Powdered Iron and Sintered Iron Driving Bands in Germany: BIOS Final Report 1323 (PB L 79189), January 1945, 120 pp.

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After many struggles, the difficulties encountered in maintaining a suitable protective atmosphere were overcome by close attention to the following operating directions:

1. The CO/CO_2 ratio of the protective gas at the various temperatures read from the 10 thermocouples distributed throughout the length of the muffle must exceed the following equilibrium values:

Temp. °C.	CO/CO_2 ratio
500	1.06
600	1.18
700	1.50
800	1.86
900	2.23
1,000	2.57
1,100	2.93
1,200	3.17

2. Pushing a car through the feed lock into the kiln or pulling it out of the kiln through the discharge lock is best done by lighting a producer gas flame in the lock before the inner lock gate is opened. With the outer lock gate also closed, the flame consumes the oxygen of the air in the lock and then goes out. Extinction of the flame is indicated by a rapid drop on an attached manometer. Not until the manometer has registered this drop is the inner lock gate opened. This procedure not only minimizes explosion hazards, but prevents any discontinuity in composition of the protective atmosphere.

3. Isolating the combustion chambers and kiln roof by plugging up the masonry cracks, especially at expansion joints, to lessen leakage of protective gas.

4. Regulating over-pressures to keep the furnace gas faintly reducing and to balance the pressure in the heating ducts against the pressure in the muffle, so that chimney gas from the heating flues cannot penetrate into the reaction chamber despite the fact that the muffle is not absolutely gas-tight.

The following gas balance, taken from the second report (No. 2008), shows how serious the leakage of producer gas may be:

The 20,000 cu. m. (706,290 cu. ft.) = 100 percent of producer gas introduced into the kiln per day is distributed as follows:

		Percent
1.	Protective gas	
	(a) Loss by leakage from heating ducts, 25%.	
	(b) Loss by leakage in the masonry and the locks, 15%	40.0
2.	Loss into the off gases at 400°C.	15.5

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	Percent
3. Loss by radiation	32.0
4. To provide heat of reaction	7.0
5. Heat lost by cooling	5.0
6. Heat lost in the charge	0.5
	100.0

FINISHING THE REDUCTION OF CENTRIFUGAL POWDERS

Two types of centrifugal powders were studied: SL and S, both made by DPG, the former carburized to about 2 percent C and the latter carbon-free. Although the experiments did not include Mannesmann powders, made by quenching a stream of molten iron in steam, it is thought that the procedure described for SL and S powders is suitable also for finishing the reduction of Mannesmann powders.

The carburized powders are self-reducing; that is, the carbon present is sufficient to reduce the oxide present and yield a product containing less than 0.1 percent C. The carbon-free powders require the addition of 3.3 percent charcoal, or 9 percent sawdust, before charging in saggers.

Table 1 shows the analyses of three such lots of carburized SL powders as received. Table 2 gives the data obtained on reduction of the first two powders of table 1 plus a third powder belonging to the same lot; the third powder of table 1 was reduced in an earlier series of runs, for which the cost calculations here reproduced do not hold.

TABLE 1. - Analyses of carburized iron powders

Total Fe, percent	Metallic Fe, percent	Degree of reduction, percent	Actual C-content percent	Specified C-content percent	Oxygen (calculated), percent
93.8	82.0	87.4	1/ 1.5	2.6	4.5
94.6	83.4	88.3	1/ 0.5	2.45	4.2
96.1	87.4	90.9	1.68	1.9	3.3

1/ Approximately.

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TABLE 2. - Finishing the reduction of carburized centrifugal powder

C-content of the raw material, percent	Average peak temperature °C 1/	Car-pushing interval, hours	Time above 800°C, hours	Degree of reduction, percent
1.69 - 1.44	945	2	8.8	97.5
	990	2	10.5	97.9
	1010	2	12.0	97.4
	1040	2	12.3	97.5
	1040	2	12.3	97.8
1.39 - 1.32	900	3	10.5	95.1
	900	3	10.5	95.3
	940	3	13.0	96.8
	955	2	9.3	96.8
0.52	980	4	18.0	96.1
	990	4	19.0	95.3

1/ These temperatures are 50° to 100°C. low, as shown by subsequent calibration of the thermocouples.

The car-pushing interval tabulated in the third column of table 2 cannot be interpreted satisfactorily without reference to the curve showing temperature distrivution along the length of the muffle. The first report (No. 2005 of ZFC) shows two such curves, which, however, pertain to early runs under conditions that proved to be unsuitable for the purpose. Obviously with 27 cars moved along one car length every 2 hours, the total time cycle, i.e., heating, reduction, cooling, would be 27 x 2 = 54 hours, whereas a 4-hour car-pushing interval would correspond to a time cycle of 27 x 4 = 108 hours. The Bureau of Mines made sponge iron from magnetite concentrate in a 200-foot tunnel kiln using time cycles ranging from 58 to 80 hours, distributed as follows:

Heating	12 hours
Reduction period (i.e., time above 900°C.)	34-48 hours
Cooling	12-20 hours
Maximum temperature	1120°-1150°C.

The time-temperature curve along the length of the Bureau of Mines kiln had a more nearly flat course during the reduction period above 900°C., whereas the two curves shown in the first German report (No. 2005) come to a sharp peak between the two 900°C. points, two car lengths apart at the 4-hour car-pushing interval. Furthermore, the Bureau of Mines kiln was direct-fired with fuel oil and coal in alternating fire boxes, which permitted regulating the heating, reduction, and cooling periods more or less independently. It is not clear from the German reports whether halving the car-pushing interval does not also halve the heating and cooling periods; but that this is so may be taken from their recommendation that on adopting the 2-hour car-pushing interval the cooling zone and the system of cooling pipes should be increased.

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The cost calculation for finishing the reduction of 500 metric tons (550 short tons) a month of carburized centrifugal powder is given in Reichsmarks (or approximately in dollars, assuming 4 RM = $1), as follows:

	RM	(Approx.)
Operating the producer:		
160 met. tons (176 short tons) coke, at RM 30 / met. ton = $6.80 / short ton, f.o.b. plant.		
For generating heating gas and protective gas, = RM 4,800 122 met. tons (134.2 short tons) steam = RM 610 at RM 5 / met. ton = $1.13 / short ton	5,410	1,353
Electrical energy		
8,600 KWH for kiln operation and lighting at RM 0.07 = 1-3/4¢ a kw.-hr.	600	150
Water for the cooling tower:		
100 cu. m. (3,532 cu. ft. = 26,417 U. S. gal.) at RM 0.30 / cu. m. = 28¢ / 1,000 gal.	30	8
Ceramic saggers:		
6,000 at RM 1.50 = 37-1/2¢ apiece	9,000	2,250
Rental of kiln and plant space	3,500	875
Labor costs:		
21 laborers at RM 300 = $75 a month = RM 6,300 5 office and tech. men = RM 2,500	8,800	2,200
Miscellaneous expenses	300	75
Total	27,640	6,911

From this, the cost for finishing the reduction of 500 metric tons a month of carburized SL powder is RM 5.55 / 100 kg. = $12.60 / short ton, not including cost of comminution but including the cost for loading the finished powder.

Here, as for the Bureau of Mines costs, one of the largest items is the cost of saggers. For these experiments, using a 2-hour car-pushing interval, the saggers were "half saggers," 39 x 18 x 11 cm. (approx. 15-1/2 inches long, 7 inches wide, and 4-1/2 inches high), 72 saggers in 6 or 7 layers per

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car. To prevent sticking, the inner walls were painted with a suspension of clay in water, which, of course, was unnecessary when making "reduction powders" from a layer of iron oxide between 2 layers of reducing agent. These saggers withstood only four trips through the tunnel kiln.

None of the four German reports gives a complete analysis of the finished product, but it may be assumed that it meets the powder-metallurgical specifications of 0.04 to 0.10 percent C and about 0.5 percent oxygen, with a bulk volume, on tapping, of 35 to 40 cubic centimeters per 100 grams.

Krebs[10/] gives the following analysis of the DPG powder used for making shell bands:

	Percent
Fe	99.5
C	0.15
O	1.5
S	0.05
Si	0.15
P	0.05
Mn	0.5
	101.90

This must be in error, for it amounts to 101.90 percent; if the specified maximum oxygen content of 0.5 percent is assumed (to replace Kreb's figure of 1.5 percent O_2), 98.6 percent Fe would bring the total to 100 percent. Krebs states that the powder has a rough spherical surface and shows the following screen analysis:

Millimeter screen opening	Approximate U. S. Mesh	Percentage by weight
On 0.300	+48	3.5
On 0.300 through 0.150.	-48 + 100	28.2
On 0.150 through 0.100.	-100 + 150	5.2
On 0.100 through 0.075.	-150 + 200	4.6
On 0.075 through 0.060.	-200 + 250	39.0
On 0.060 through 0.050.	-250 + 275	10.5
Through 0.050	-275	9.0

10/ See footnote 8.

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REDUCTION OF ROLL SCALE

Three lots of roll scale were reduced in the Bremen tunnel kiln. Table 3 shows their analysis:

TABLE 3. - Analyses of roll scale

Source, tons	Bruex 20, percent	DPG 8, percent	Denmark 600, percent
Fe (total)	74.30	75.25	72.7
Fe (ferrous)	49.68	52.80	-
Fe (metallic)	.63	.29	-
SiO_2	.65	.17	1/ 0.68
Cu	.06	.015	
S	.034	.02	
P	.02	.037	
C	.20	.15	

1/ Residue.

Only the Danish roll scale was used to determine whether so-called "reduction powders," made by reducing iron oxides, would also give satisfactory results when using "half saggers" containing one thinner (about 40mm. = 1.57 inch) layer of oxide between two layers of peat coke (instead of charcoal) and run at the shorter two-hour car-pushing interval (54-hour time cycle). Only the -6 mesh fraction of roll scale was used, the larger fractions being rejected. The plant had to shut down April 1945 because of increasing enemy activity, and only six cars of finished product could be obtained. This was considered sufficient to demonstrate that "reduction powders" also could be made at the greater kiln capacity resulting from the changes in technique listed above, and the following cost estimate is given for making 105 metric tons (115-1/2 short tons) per month of reduction powder.

	RM	$ (approx.)
Operating the producer:		
190 met. tons (209 short tons) coke, f.o.b. plant.		
at RM 30 / met. ton = $6.80 / short ton = RM 5,700		
For generating heating gas and protective gas.	6,425	1,606
145 met. tons (159-1/2 short tons) steam,		
at RM 5 / met. ton = $1.13 / short ton = RM 725		
For operating the producer.		
Electrical energy:		
8,600 kw.-hr. for kiln operation and lighting		
at RM 0.07 = 1-3/4¢ a kw.-hr.	600	150

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	RM	$ (approx.)
Water for the cooling tower:		
100 cu.m. (3,531 cu. ft. = 26,418 U. S. gal.) at RM 0.30 per cu.m. = 28¢ per 1,000 gal.	30	8
Ceramic saggers:		
4,000 at RM 1.50 = 37-1/2¢ apiece	6,000	1,500
Peat coke:		
35 met. tons (38.5 short tons) at RM 70 per met. ton = $15.91 per short ton	2,500	613
Rental of kiln and plant space	3,500	875
Labor costs:		
21 laborers at Rm 300 = $75 a month, RM 6,300) 5 office and tech. men RM 2,500)	8,800	2,200
Miscellaneous expenses	300	75
	28,155	7,027
Credit for reaction gas, 38,400 cu.m. (1,356,000 cu. ft.) = 10 met. tons (11 short tons) coke at RM 30 = RM300) **Credit** 7.6 tons less steam consumed at RM 5 = RM 38)	338	84
Total	27,817	6,943

This means RM 26.25 per 100 kg. = $59.63 per short ton for making 105 metric tons a month of reduction powder, excluding cost of comminuting the roll scale and the finished product but including loading cost for the product.

These two cost figures, $12.60 and $59.60 a ton for SL-powder and reduction powder, respectively, are about 60 percent of the corresponding figures obtained previously by use of the larger saggers, thicker layers of oxide, and bulky charcoal (instead of the denser peat coke), with a car-pushing interval of 4 hours. Increasing enemy activity forced a shut-down of the plant at this early stage of the kiln-capacity tests, and hence the following table 4 is included to present additional data on the reduction powders that resulted from the runs described in the second German report (No. 2008) when the kiln was operated on the original 108-hour time cycle, and the larger saggers were charged either by the mix method or with two 60-mm. (2.36-inch) layers of oxide alternating with three layers of charcoal as reducer.

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TABLE 4. - Reduction of iron oxides

Material	Reduction temperature °C.[1]	Oxide C, mixed: Volume, cc/100 gm.	Oxide C, mixed: Degree of reduction, percent	Oxide C, in layers: Volume, cc/100 gm.	Oxide C, in layers: Degree of reduction, percent	Remarks
Magnetite Concentrate	925	103/70	71	-	-	
	950	-	-	85/60	93	
	970	90/63	95	-	-	Closed capsule.
	1040	-	-	80/60	96.8	
	1030	-	-	66/51	95.5	
	1045	-	-	80/58	97.9	Little closed boxes.
	1060	-	-	67/50	97.4	In one layer.
	1070	-	-	65/49	97.8	Ground peat coke.
Roll scale, from Bruex	900	92/66	83	-	-	
	950	88/65	88	-	-	
	950	85/65	90	-	-	
	965	93/67	92	-	-	
	970	77/55	93	-	-	
	1000	80/59	95	-	-	
	1005	81/62	94	76/55	97.2	
	1040	-	-	78/59	97.5	
	1030	-	-	75/55	96.8	
	1045	-	-	74/56	98.3	Little closed boxes.
	1060	-	-	70/54	97.8	In one layer.
	1070	-	-	62/46	97.3	Ground peat coke.
Roll scale, from DPG	945	133/89	78	-	-	0.08% C.
	950	-	78	97/65	93	0.10% C.
	970	90/63	94	-	-	
	1015	105/75	95.5	-	-	
	1025	93/67	95.7	84/61	97.2	
	1030	97/70	94.9	73/55	97.4	
	1040	90/67	95.0	-	-	
	1045	-	-	65/50	97.6	
	1045	-	-	72/53	98.5	Little closed boxes.
	1060	-	-	60/46	97.6	
	1060	87/66	96.5	-	-	
	1065	91/67	95.8	-	-	
	1070	-	-	60/47	97.8	Ground peat coke.
	1075	-	-	60/45	97.3	

1/ All these temperatures are 50° to 100° too low, according to subsequent calibration.

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The Swedish magnetite concentrate from Boliden had the following composition:

	Percent
Fe (total)	66.35
Fe (ferrous)	11.19
Fe (metallic)	Trace
SiO_2	6.85
Cu	Trace
S	0.03
P	0.01
C	0.34

The upper figure of the specific volumes given in table 4 refers to the volume occupied when 100 grams of the powder is poured into a container (probably in some particular way, as specified by powder metallurgists), whereas the lower figure refers to the final volume when this container, with its contents, is tapped.

The fourth report describes a brilliantly conceived series of laboratory experiments that show clearly that, other factors remaining constant, the time required for complete reduction varies directly as the square of the thickness of oxide layer, although the straight line expressing this relationship does not go through the origin (abscissas are proportional to the square of layer thickness). The author's interpretation, that optimum operating conditions are found at the point where the velocity of the chemical reaction is just equal to the rate at which heat is conducted to the oxide layer, although probably true for the three series of laboratory experiments presented, cannot be applied to the operation of the Bremen kiln as simply and unqualifiedly as is done by the author, Dr. H. Ley. This is obvious from Ley's figure 2, which shows the two points established in the Bremen kiln for 30 and 65 mm. layers, which occur at 4 hours and 8 hours heating, respectively; that is, doubling the layer requires only 1.8 times the heating period. The explanation of this discrepancy is simply that in the laboratory experiments the initial heating up to the reduction temperature and the final cooling down to room temperature are done in an oxygen-free atmosphere of nitrogen and are absolutely identical in all the runs; whereas, at Bremen, going from a 4-hour to a 2-hour car-pushing interval also halves the times of heating and cooling, not to mention the changes in sagger dimensions and reducing agent. Therefore, the claim of a further increase of 20 percent in kiln capacity deduced from these laboratory experiments requires confirmation on the larger scale. In fact, it is not made clear why the runs with 65 mm. layers at the 4-hour car-pushing interval and with the larger saggers failed to be satisfactory economically; computation shows a larger tonnage per day was produced at the 108-hour time cycle, using 60 large saggers, which cost as much as the 72 "half saggers" used at the 54-hour time cycle. The time for loading and unloading the smaller number of large saggers should have been less, and the troublesome routine at the locks would have been cut in half, compared to the 2-hour interval.

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This fourth report implies, also, that the fact that Hoeganaes sponge iron comes in 30 mm. disks confirms their finding that this thickness of layer is optimum. The latest description of the Hoeganaes procedure[11] shows rectangular cakes, 375 x 250 x 60 mm. (approx. 14-3/4 x 9-3/4 x 2-1/4 inches) obtained by their new method, in which magnetite concentrate formerly charged in alternating horizontal layers is now charged in vertical cakes. Even before the Swedes, the Bureau of Mines adopted canister charging and pug charging of vertical "pigs" of iron ore surrounded by a reducing mixture containing 15 percent limestone. Ekelorp does not mention limestone, probably because the 30 percent ash of their coal contains calcium carbonate; but Tigerschiold,[12] in his description and cost figures for the early phases of the Hoeganaes process, gives 190 kg. of limestone to 800 kg. coke breeze as reducing mixture for 1,420 kg. of 70 to 71 percent magnetite superconcentrate to make 1 metric ton of sponge iron analyzing 96 to 96.5 percent Fe, 1.5 to 2.0 percent O_2, and 1.5 to 2.0 percent gangue. The Bureau of Mines considers that limestone originally added simply as a desulfurizing agent, has more important functions as a factor in the successful manufacture of brickyard sponge iron, and it is pertinent to ask whether reduction powders could not be made in a direct-fired ceramic tunnel kiln such as was used for making Hoeganaes-type sponge iron during the war. In other words, mixing 15 to 20 percent limestone with the reducing agent should avoid the necessity of a muffle, together with all the complications and expense encountered in maintaining a protective atmosphere.

From the reports on the experiments in the Bremen kiln, it seems that the sponge iron "pigs" made by the Bureau of Mines could be crushed and ground to powders that might be suitable for powder-metallurgical purposes. The four German reports are somewhat contradictory on this point. In the second report (No. 2008), on page 9, it says:

"As compared with centrifugal powders, the blocks of reduction powders have a smaller bulk-density and are very spongy, and hence readily comminuted," and on page 11:

> The specific volume, after tapping, decreases with increasing temperature, as desired. At the maximum temperature, bulk volumes on tapping were 45 to 50 cc. per 100 grams. Extrapolation indicates that a further increase of 50°C. in maximum temperature should certainly suffice to attain the specified bulk volume of 35 to 40 cc. per 100 grams in the case of reduction powders.

11/ Sven Ekelorp, The Hoeganaes Sponge Iron Process: Jernkontorets Annaler, vol. 129, No. 12, 1945, pp. 703-721. See fig. 13 on p. 717.

12/ Magnus Tigerschiold, The Sponge Iron Problem: Blad foer Bergshandteringens Vaenner, vol. 20, 1932, pp. 219-289.

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Degree of reduction increases with temperature, reaching an optimum at about 1025°C. It should be stated here that standard specifications allow higher contents of oxygen in reduction powders.

On the other hand, in the third report (No. 2010), in featuring the advantages of their procedure over that used at Hoeganaes, they say of the Swedish sponge iron cakes (p. 12):

> ***an oxygen content as low as that of Bremen powder can be obtained only at higher temperatures, and hence they are more difficult to grind.

The four German reports are significantly silent as to crushing and grinding technique.

Comstock[13] makes the following statement:

> The annealed powder on being taken from the furnace was in the form of brittle cake. It was broken out from the trays and crushed and sieved in a standard plant embodying jaw crusher, rotary drum pulverizer, and vibratory screen coupled with the usual elevator gear. Unsintered scrap rings were put back into powder form by first breaking in a specially designed crusher and then pulverizing in a standard rotary type grinder and screening.

Krebs[14] has the following description of the powder mill:

> Iron and other metals and alloys which are to be pulverized may be fed into the mill in various forms, such as wire, granules, chips, borings, shavings, turnings, or crushings.
>
> The pulverizer is built on the well-known principle of the beater or hammermill type, in which the resulting particle size is governed by the length of time of treatment and the mesh size of the screen at the discharge end.
>
> The material is introduced into the mill by means of a continuous feeder. Two propellers or beaters, made of hard sintered metals or of manganese steel of great hardness, whirl the metal particles against one another. By this impact they break up into powder form. In order to keep the powder in constant suspension so as to continually expose the powder to the action of the hammer as well as to prevent oxidation from the air, a constant stream of inert gas is fed into the disintegration chamber. Particles of sufficient fineness are

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13/ See footnote 8.
14/ See footnote 9.

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continuously discharged through a screen. The shape and size of the particles are governed by the speed and spacing of the hammers. The iron particles have a characteristic ("Tellerstruktur") disk or plate shape.

Ivery,[15] discussing Mannesmann powders, shows the difference in results when grinding in a mortar and in a small roller mill. According to Ivery, ball-milling this type of powder proved unsuitable, and eventually a fluted roller mill, as used with other powders, was adopted.

The fact that the Hoeganaes corporation began advertising iron powder in 1946 and a recent statement that much of this Swedish iron powder was shipped to the United States during the war[16] are circumstantial evidence that the Hoeganaes procedure can be adapted to the making of sponge iron suitable for grinding into a powder that would be acceptable to the powder-metallurgical industry. The details are nowhere published, but the paragraphs quoted below in translation from Swedish sources, indicate that the super-concentrate of Swedish magnetite, already as rich as 70 percent Fe, is further purified from gangue material by a new magnetic separator actuated by a three-phase alternating current (so-called "rotating field"),[17] [18] and that the resulting gangue-free magnetite is then reduced at a temperature higher than usual, and finally powdered by a specially developed grinding technique.

Sven Eketorp, superintendent of the Hoeganaes plant, in discussing Moertsell's[19] paper on iron-ore beneficiation, says:

I want to report on some work that has been done during the past two years at Hoeganaes on a commercial alternating-current magnetic separator which might be used to separate locked and unlocked grains ***. The largest apparatus built to date is 1 meter wide and can handle about 1 ton an hour, but this capacity could probably be increased, chiefly by using a frequency higher than the 50 c.p.s. at which the separator operates at present.

15/ See footnote 10.

16/ In December 1947, Swedish iron powder was said to be selling in the New York market for 9¢ a pound.

17/ Eketorp, S. G. H., and Varming, V. H., Method and Apparatus for the Dry Separation of Ferromagnetic Material, Such as Ferromagnetic Ores, Sponge Iron, and the Like: Application No. 4074/44 for Swedish Patent. For abstract, see Jernkontorets Annaler, vol. 131, 1947, No. 10.

18/ Dean, R. S., and Davis, C. W., Magnetic Separation of Ores: Bureau of Mines Bull. 425, 1941, p. 189, Lists 10 patents on A.C. magnetic separators, the earliest, Nov. 3, 1891, specifically intended for separating gangue from magnetite; pp. 190-191 list other rotary magnetic-field separators under classes 3, 5, and 6.

19/ Moertsell, Sture, Efforts Towards Rationalization in Swedish Iron Ore Beneficiation: Jernkontorets Annaler, vol. 130, No. 9, 1946, pp. 269-460. Discussion, pp. 460-476. Eketorp's discussion on pp. 467-469.

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Eleven examples are cited, of which the following three will suffice to show how the new separator breaks a magnetite concentrate into three fractions, of which the first can be made to be wholly free of particles of gangue, whereas the middlings may still be a high-grade concentrate, and most of the gangue is in the tailings.

	Percent by weight	Percent			Yield of iron, percent
		Fe	S	P	
Dalkarlsberg, maximum: grain size 0.8 mm.:					
Feed	-	47.9	0.005	0.107	-
First grade	18.1	71.0	.002	.007	26.6
Middlings	37.4	67.4	.008	.016	52.2
Tailings	44.5	23.0	.001	.224	21.2
Sum ...	100.0	48.2	0.004	0.107	100.0
Dalkarlsberg, finished concentrate:					
Feed	-	66.1	0.005	0.016	-
First grade	50.9	70.1	.002	.005	53.5
Middlings	41.2	66.0	.008	.012	40.8
Tailings	7.9	47.7	.002	.072	5.7
Sum ...	100.0	66.7	0.005	0.013	100.0
Asboberg, finished concentrate:					
Feed	-	67.0	0.001	0.003	-
First grade	88.2	70.7	Trace	.001	92.8
Middlings	8.0	51.9	0.020	.006	6.3
Tailings	3.8	15.6	.082	.023	0.9
Sum ...	100.0	67.1	0.005	0.002	100.0

A further source of information on Hoeganaes sponge iron is the recent paper by Tigerschioeld,[20] in which the following paragraph occurs on page 297:

Immediately after the beginning of the second world war, Hoeganaes made an extra-enriched, more highly reduced sponge, which was delivered in powder form and had extensive application, especially in America, for making pressed and sintered iron objects. It seems as if this product will meet with ever-increasing demand.

If the above surmizes as to the way Swedish iron powder is made are correct, producers of magnetite concentrate might well consider extending the Bureau of Mines experiments on brickyard sponge iron to include the production

20/ Tigerschioeld, Magnus, The Use of Sponge Iron in Swedish Steel Making: Jernkontorets Annaler, vol. 131, No. 9, 1947, pp. 295-339. Discussion, pp. 339-371.

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of iron powder. Where magnetite ore is already being beneficiated by magnetic separators, the installation of a 300 to 500-foot direct-fired tunnel kiln having a maximum capacity of 35 to 60 tons of sponge iron a day[21] could meet a possible future demand for 5¢- to 6¢-a-pound iron powder suitable for making articles by powder-metallurgical methods. The ease of procuring cheap coke breeze or cheap buckwheat anthracite, both of which have proved to be satisfactory for solid-fuel reduction of magnetite, and the indicated possibilities for further mechanization of the tunnel kiln procedure are factors favorable to the economics of such production, however difficult and costly the final crushing and grinding of sponge-iron pigs may prove to be. The spread between prices of highest-quality Swedish sponge iron ($73 a ton) and 9¢ Swedish iron powder ($180 a ton) would seem to be large enough to cover costs of comminution and of making a special super-concentrate by use of the rotating-field magnetic separator.

21/ About 10 percent more if the German device of a system of air-cooled pipes is applicable for steady production.

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